Reprinted from
ANNUAL REVIEW OF BIOPHYSICS AND BIOENGINEERING
Vol. 1, 1972

MONITORING OF PHYSIOLOGICAL DATA IN A CLINICAL ENVIRONMENT

9007

Reed M. Gardner

University of Utah, Latter-day Saints Hospital, Salt Lake City, Utah

INTRODUCTION

Following the great technological developments made during the 1940s and subsequent medical developments in instrumentation made in the late 40s and early 50s, monitoring of many physiological variables has become a reality in both research and clinical settings. Intensive care units (ICU) for the treatment of acutely ill patients in various states have evolved rapidly and gained wide acceptance. With the introduction of analog computers in the late 50s and digital computers in the 60s, applications of these machines to physiological monitoring in surgical suites and intensive care units have greatly enhanced the power and flexibility of instruments. Primary emphasis of this article will be to review the quantitative measurements used to affect diagnostic and therapeutic decisions of the physician as he manages the high-risk patient in the intensive-care unit. Since the computer has become an integral part of the more sophisticated and pioneering intensive-care units, a significant part of this review will be directed toward computer applications.

OBJECTIVES

The long-term objective of monitoring physiological data is to decrease mortality and morbidity by: (a) measuring data automatically on a real-time basis for analysis and decision making; (b) processing the data to set alarms; (c) providing control and feedback information for therapy; (d) suggesting therapy based on automated data entry; (e) providing insight into disease processes through research applications; (f) providing better care with fewer staff members; (g) organizing and displaying information in a form meaningful to improved patient care; and (h) correlating multiple parameters for clear demonstration of clinical problems.

PHYSIOLOGICAL SIGNALS

The search for the most significant physiological variables to measure has just begun. It should be apparent that no single physiological variable provides sufficient diagnostic and therapeutic information to be the only variable monitored (1–6).

A multitude of physiological signals can and are being measured in various laboratories, but to perform these measurements in a clinical setting poses the following questions: (a) Can the procedure be brought to the bedside, since critically ill patients often cannot be moved? (b) Does the test or measurement have clinical value? (c) Can the patient tolerate the procedure if it involves blood loss or trauma? (d) Is the maximum amount of information made available from the fewest number of sensors with the least disturbance to the patient? (e) Does the measurement need to be made continuously or if intermittently, how frequently? (f) Is the patient made immobile and/or uncomfortable by the measurement? (g) Can the measurement be made simply and reliably over an extended time interval? (h) Can the procedure be economically justified on a cost-effectiveness basis?

General characteristics of physiological instrumentation that answer some of the problems are those that are: (a) simple; (b) easy to use; (c) stable; (d) inexpensive; (e) safe; (f) reliable—having a long interval between failures; (g) easily calibrated and tested; (h) able to present signals for multipurposes, viz, bedside display, computer analysis, or transmission to remote site. With these questions and characteristics in mind, "state of the art" monitoring techniques covering the following four areas will be explored: (a) cardiovascular; (b) pulmonary; (c) fluids, electrolyte balance, and body weight; (d) general clinical observations.

Cardiovascular

Indirect blood pressure.—Clinical evaluation of the functioning of the cardiovascular system depends to a large extent upon the measurement and interpretation of blood pressure. The measurement of indirect blood pressure has changed little since the early 1900s. Technique and problems are clearly explained in the American Heart Association's recommendations for human blood pressure determination by sphygmomanometers (7). Excellent reviews of available direct and indirect blood pressure measuring techniques are contained in a book by Geddes (8) and an article by Fink (9).

One notable development in the measurement of blood pressure indirectly is the application of the Doppler ultrasonic sensor (10) for measurement of vessel-wall movement for detection of systolic and diastolic pressures. Recently, a commercial version of this equipment has become available. Comparisons between the ultrasonically sensed and directly measured arterial pressures have been made (11) on patients following cardiovascular surgery. Correlations seem to be good, but at the moment the expense of the instrument precludes its use in many situations.

Virtually every indirect measurement of blood pressure requires inflating a cuff to stop blood flow and suffers from many problems (7, 8, 12, 13). Frequent pumping of a cuff can cause edema and engorgement, leading to invalid results and discomfort to the patient. During hypotension and shock, Korotkov sounds are difficult to hear and result in invalid pressure readings (7, 9, 12).

Direct arterial blood pressure.—Many significant developments have been made recently in the measurement of intra-arterial blood pressure directly. More and more clinical centers are realizing the limitations of indirect pressure and realizing the advantages of measuring direct arterial pressure (12–18). Problems of surgical procedure (19) and cut-down necessary to insert arterial catheters have largely been eliminated. Catheter clotting and dynamic response limitations due to catheter-transducer system characteristics have been studied and can be minimized by proper techniques. Simplified techniques have greatly improved signal quality and increased the trouble-free interval of recording. It is now common practice to insert central and peripheral arterial catheters percutaneously and attach transducers directly at the patient. Latter-day Saints Hospital has extensive experience with central arterial catheters, with a history of over 4500 insertions and 12,000 patient days in intensive care with minimal complication (less than 0.2%). This has been made possible by three developments (20): (a) a simple percutaneous cannulation technique; (b) development of a continuous flush system that causes minimal signal distortion but enables the catheter to be flushed continuously and provides the mechanism for testing the catheter system's dynamic response to a step change in pressure; (c) development of simple, stable electronics at the bedside that nurses and technicians can easily operate (21, 22).

The direct-pressure method gives not only systolic, diastolic, and mean pressures but also visualization of the pulse contour and such information as stroke volume (17), duration of systole, ejection time (23), and other variables. Once an arterial catheter is in place it is also convenient for drawing blood samples to determine blood gases, dye dilution curves, and chemistries (20).

Although most centers use peripheral pressures determined by needle cannulation, evidence suggests that central arterial pressures are a more valid representation of the patient's physiological state.

Venous pressure.—Monitoring of central venous pressure has become an accepted technique in the management of acute circulatory failure and maintenance of blood volume in difficult fluid balance problems (24, 25). As with arterial cannulation, venous cannulation is not without complications and technical pitfalls (26). However, development of cannulation techniques and simple equipment checks have greatly reduced complications and assisted in management of patients. Simple water manometers are the most common measuring device in use. Pressure transducers have been used extensively and many available transducers are adequate for measuring central venous pressure. Useful information is clearly derivable from the ventral venous pressures (16, 17, 27, 28).

Problems still to be resolved in measuring central venous pressure are (a) hydrostatic pressure variations due to positioning of the transducer, since the transducer cannot be economically placed at the catheter tip and small, positional changes cause large errors in venous pressure (range 5–20 cm H_2O); (b) infusing intravenous fluids while measuring pressure through the same catheter.

Pulmonary artery pressure.—Recent catheter developments have opened an exciting new area of monitoring. Development of the Swan–Gantz catheter

(29, 30), a balloon-tipped, flexible catheter that can be flow directed from a peripheral vein into the pulmonary artery, has made routine clinical monitoring of pulmonary artery pressure possible. With this catheter, either pulmonary artery wedge pressure, measured by inflating the balloon at the catheter tip, or end diastolic pressure in the pulmonary artery, gives a good indication of left atrial pressure, which is very valuable in predicting and treating left ventricular failure in myocardial infarction or surgical patients (31).

Left atrial pressure.—Most commonly, left atrial pressure is measured on cardiovascular surgery patients when a left atrial pressure cannula can be placed. Normally, these cannulae are discontinued 24 to 48 hours following surgery (14, 15). Technical problems are very similar to those experienced when measuring pulmonary artery and venous pressures.

Blood flow.—Measurement of blood flow (cardiac output) and stroke volume have become a major considerations in the management of patients in intensive care (14–17, 32–36). The most widely used technique is the indicator dilution technique using indocyanine green. The dye is injected into the right atrium or pulmonary artery and dye concentration is measured at an arterial site by withdrawing blood through a cuvette system. This technique can be done rather simply, and automated techniques for calibration and computerized calulation have been implemented (33, 37, 38).

In recent years, the thermal dilution technique has gained popularity for the following reasons: (a) only one catheter is inserted into the circulation and no blood is withdrawn (especially important when monitoring infants); (b) only physiological fluids are injected, eliminating complications of other colorimetric techniques; (c) recirculation effects are minimized; (d) transducers are small and fast. Discussion of limitations of this technique are reviewed in a recent article by Wessel and associates (39).

The Fick method for measurement of cardiac output (111) has been implemented clinically in only a few laboratories because of the difficulties in gas sampling and in determining the arterial and venous blood oxygen content.

The pulse contour technique developed by Warner (16, 17) gives an estimation of beat-to-beat stroke volume and has been used for both short- and long-term monitoring of several types of patients. The technique has limitations, but has been extremely useful in monitoring the critically ill and in planning therapy for these patients (36, 40). Changes in cardiac output can be followed very reliably for periods of at least 24 hours, and then, on some patients, recalibration is necessary (41). Utilization of the central arterial pressure to calculate stroke volume and cardiac output is of great advantage for monitoring patients, since it requires only a central arterial catheter through which measurement can be made continuously or intermittently, as the situation demands.

Electrocardiogram (ECG).—There have been a number of attempts in the last ten years to develop automated classification schemes for detecting life-threatening cardiac arrythmias, especially in myocardial infarction patients.

Because of the high cost of continuous ECG monitoring by digital computer, two approaches have been taken: (a) development of hybrid and special purpose processors; (b) intermittent sampling for rhythm with continuous display of rate for alarm function. Most of these attempts have been directed at detecting arrythmias using classification criteria similar to those applicable to a visually observed ECG monitor (42–45).

Most ECG rhythm systems (47) will work reliably with high-quality signals, but there are misclassifications when artifacts are present. Fundamental problems therefore in automated measurement of rhythms are the patient electrode interface and artifacts caused by patient movement (46).

An interesting scheme that allows the nurse or physician to visualize rhythm changes is described by Webb (48). When each R wave of the ECG is triggered, a contour map can be produced on a storage oscilloscope or on a graphical recorder. A human observer viewing the pattern can easily pick out rhythm changes, rate changes, aberrant beats, and other significant abnormalities.

Temperature.—The determination of body temperature by manual or automated methods is important in determination of septicemia, peripheral vascular perfusion, and as an indirect indication of certain physiological changes (14, 15). Joly & Weil (94) have used temperature of the great toe as an indication of severity of shock. Instrumentation for temperature measurement generally uses thermistors as sensing devices in the clinical environment.

PULMONARY

Respiratory insufficiency is a major cause of postoperative and posttraumatic death. There is a large class of patients who need respiratory monitoring (49, 50). Developments in pulmonary monitoring are especially important since it is difficult for the human observer to make direct quantitative assessments of pulmonary function. Several laboratories and clinical centers have implemented pulmonary monitoring. The work of Osborn (15, 51–58), Peters (59–61), Lewis (62, 63), Dammann (64–67), and their colleagues gives a cross section of the type of pulmonary monitoring that is currently in use. The following specific areas are of primary importance.

Blood gases.—Semiautomatic and automatic techniques have been devised for sampling and determining blood gases (PCO_2, PO_2, pH) (68, 69). The work of Eberhart (70) is an example of a scheme that requires the nurse to draw samples and then insert the sample into the system for automated measurements. More recently, Clark & Veasy and their associates (71, 72) have developed a system for automatic withdrawal, sampling, and display of arterial and venous blood gases. The recent introduction of miniature O_2 and CO_2 sensors (73) for continuous intravascular monitoring of PO_2 and PCO_2 has provided the physician and staff with moment-by-moment analysis of respiratory gases in order to implement therapy and determine patient status (74). Estimates of arterial blood PCO_2 can be obtained from end tidal (alveolar) respiratory gas sampling (75, 76).

Tidal volume and minute ventilation.—One of the simplest techniques makes use of the spirometer on the outlet line of a respirator. This spirometer is valved such that it empties during inspiration and fills on expiration. Techniques have been devised that give the spirometer rate and tidal volume alarm capabilities (77).

The primary instrument used for the measurement of gas flow is the Fleisch pneumotach (15, 59, 65). This instrument has been adapted for clinical situations but has the disadvantage that it requires multiple lead attachments and is subject to plugging if used for long-term monitoring. The recent development of an ultrasonic flowmeter holds promise for more clinically realizable intensive-care monitoring (78–80). Flowmeter signals are integrated to obtain tidal volume and minute ventilation. Commercially available packages are now being produced that permit implementation of respiratory flow and volume monitoring (61, 78).

Respiratory rate.—Respiratory rate is easily determined from respiratory flow signals. Rate can also be measured using impedance plethysmography techniques using the electrocardiogram electrodes as a signal source (81).

Oxygen uptake.—Measurement of the amount of oxygen consumed has potential value in determining the metabolic state of the patient (54, 58, 82). The general approach to measuring O_2 uptake is to measure air flow and oxygen concentration simultaneously during inspiration and expiration. Flow is measured with a flowmeter and oxygen content may be measured with a Westinghouse oxygen cell (15) or a mass spectrometer (83). If the product of flow and concentration is integrated, inspired O_2 and expired O_2 can be computed. Subtraction yields O_2 uptake per breath.

Carbon dioxide output.—A similar technique is used for measuring CO_2 output. An infrared analyzer is usually used to measure the CO_2 concentration. Mass spectrometers (80, 83, 84) have been developed that allow measurement of O_2, CO_2, water vapor, nitrogen, and other gases used in respiratory testing. These are now in clinical application. The ability to use a single instrument to measure several gases eliminates many of the calibration and variable time delay problems associated with other techniques.

The automation of spirometric gas collection techniques has now made it clinically practical to measure oxygen uptake and CO_2 output using slowly responding sensors, thus simplifying gas exchange computation (61).

Resistance, compliance, and work.—Measuring these parameters and following them at regular intervals (four hours) can lead to early respirator support and prevent the development of complicated postraumatic respiratory distress syndrome (61). Several techniques using intraesophageal balloons and pressure sensors at the mouth have been used to estimate mechanical properties of the lung

(55, 85, 86) and the work of breathing. The work of Osborn (15), Peters (59–61), and Lewis (62), represent the outstanding clinical progress made in this area.

Venous O_2/*arterial* O_2 *saturation measurement.*—Fiberoptics catheters through which oxygen saturation can be measured by reflection oximetry (87, 88) have recently become clinically practical. With this technique, it is now feasible to measure arterial and venous oxygen saturations continously. Reflection oximetry, although it does not provide for CO_2 and pH measurements, is an adjunct to the normal monitoring of respiratory gases since it can be obtained continuously without withdrawing blood samples. Fick determination of cardiac output is potentially implementable using this technique and oxygen uptakes discussed earlier.

Tissue and regional perfusion.—Various techniques, most of them centered around a mass spectrometer (89, 90), have been used to measure tissue and regional blood gas compositions. These sensors are slow, requiring 20 sec to 1 min per analysis. The slow speed however is adequate for determination of tissue perfusion.

Fluids, Electrolyte Balance, and Body Weight

Intake.—Normally, fluid intake is determined by measurement of amount of volume given in the patient's food and by manually or semiautomatically measuring intravenous infusions. There are no automatic techniques reported for fluid intake measurement.

Output.—Measurement of output fluid volume is commonly made manually from a collection system. Sheppard (91, 92) and Meagher (93) have attempted to automate urine and drainage tube volume outputs. Computer algorithms used to calculate insensible losses from skin and respiration are based primarily on body/room temperature differences (110). Measurement of electrolytes (calcium, potassium, sodium, chloride) through semiautomatic techniques (2, 71) is now becoming possible using electrodes and ion exchange resins.

Body weight is of critical importance in assessing critically ill patients. It gives indication of fluid balance and can suggest edema formation (49). Measuring body weight with present techniques is cumbersome, at best, and is an area where engineering innovations are required.

Clinical Observations

Many of the automated and semiautomated techniques discussed above are not, at present, applicable to some very fundamental and necessary observations upon the patient (16, 17, 99). For example, none give indications as to patient history, which contains pertinent information for diagnosis and treatment. Other clinical observations made by physicians, such as auscultation of the heart and lung area and observation of X-ray information for detection of heart borders and condition of the lung, are not available through normal automated clinical monitoring procedures. These, in addition to the verbal communication from the patient to the physician, are not amenable to automated techniques. However, any automated or computer technique must take this information into consideration in order to be most effective.

ELECTRICAL SAFETY

With the increase in number and types of equipment located at the bedside, the possibility of electrical shock has become a very serious problem (95–98). The patient with the pacing catheter attached to an external pacemaker is the most electrically susceptible. Patients with fluid-filled catheters are next most susceptible, but by an order of magnitude less because of the high resistance of the fluid-filled column and the fact that the catheter tips are not normally placed in direct contact with the myocardium.

SIGNAL PROCESSING

With the multitude of physiological signals available and the minute-by-minute variations that can take place in patients in intensive care, it is imperative that signals be processed to make them readily interpretable by the person required to make the clinical decision—often a nurse, intern, or resident. There are three approaches to such processing of physiological signals: (a) analog processing, using linear or nonlinear amplifiers; (b) processing with both analog and digital processing in the same package; (c) digital processing in which the digital signal is normally derived from analog preprocessed signals.

In the case of digital processing there are multiple approaches and the application of each appears to be dependent on the technology available locally. These approaches are: (a) large-scale, time-shared computer processing where all of the algorithms are continued within the system software (15, 56, 100); (b) small-scale computer processing with software algorithms (42, 61); and (c) hardware programmed algorithms that make use of a limited amount of data storage and use fixed hardware algorithms to process the physiological signals. At the present time the first and second type processors are in most widespread use. Developments of clinically acceptable algorithms, however, will likely lead to more of the third type of processing.

A basic underlying question related to the processing of physiological data in any setting concerns the frequency of acquisition of the data and their clinical disposition (14, 15, 40, 61, 64). This problem is similar to many engineering problems in that compromises are required. On the one extreme, continuous measurement of physiological variables is indeed possible, and can easily be quantitated, stored, and displayed. However, practical experience has shown that to display and store variables at this rapid rate is both expensive and unsatisfactory from the user's point of view. If one takes the central arterial pressures as an example, there are at least ten parameters that can be calculated from this waveform, including systolic and diastolic pressure. By taking beat-by-beat variations, these ten parameters would be available approximately every second and could easily overwhelm computer storage capacity and any display device.

One exception to the above point of view occurs during surgery or following acute trauma when operative or procedural changes are occurring at rapid rate. In these cases, review of the raw data by analog display is more helpful than computed results. For most patients in intensive care, however, except for acute transient periods, we have found that automatic measurements of cardiovascular variables every 15 minutes, with operator-actuated measurements available continuously, provide adequate information on the state of the patient (40). Intermittent sampling of physiological signals is now the rule for automated clinical units (14–16, 61), the exception being ECG rhythm monitoring and the work of Dammann and associates (64). Time intervals for cardiovascular sampling are normally between 2 and 15 minutes and undoubtedly will eventually be determined by the economic considerations (42, 101).

DISPLAYS

Physiological monitoring in a clinical setting requires displays that are simple to use and easy to understand. Our experience has shown that for arterial and venous pressure, direct calibrated bedside instrumentation and oscilloscopes are necessary for displaying unmodified pressure signals. Bedside instrumentation provides rapid quality checks and system backup. Graphical recorders are a necessity for studying arrythmias and various other physiological waveforms.

One of the most challenging areas in the medical application of computers is to develop techniques for optimal display of derived information (14–17). The computer is able to collect and store a mass of information. Displaying the information to the user—usually a physician or nurse—requires very careful consideration. Our group and several other groups have gone through several iterations in generating displays of physiological data. We find that numerical as well as graphical data is important. Evaluation of the various types of displays has shown that displaying data in graphical form makes trends and acute changes more visible, thereby permitting clinical judgments to be made more easily. Rapid recall of information is also very important and is made practical by using a simple bar graph display (102).

The decision as to whether the display should be located at the bedside or at the central terminal in the intensive care unit depends on the user's philosophy. Our concept (16, 17, 40) has been that the bedside equipment and display should be simple and relatively uncluttered and that the central unit should be more sophisticated and allow for physician-nurse consultation. However, others (14, 15) have taken a different approach and have only bedside units, requiring all data entry and retrieval to take place at the bedside. Newer monitoring systems are being designed with simple display and data entry capability at the bedside with the central console used for detailed discussion on a particular patient without cluttering the bedside area and unnecessarily alarming the patient in the critical care area.

The ability to store and retrieve data offered by the digital computer is one of the most powerful augmentations to monitoring equipment (103). It has been our observation that hard-copy reporting is necessary in intensive care and surgical procedures to: (a) provide a permanent legal record; (b) form a research base for studying patients; (c) provide a tool for treatment of the patient. However, it has also been observed that continuous treatment of the patient depends directly on timely and frequent information preferably recoverable on demand; reports generated at shift intervals of about eight hours are of limited value in patient care. To make the medical record available in a timely fashion, it is necessary to enter the entire patient record into the computerized system. For example, if a drug is given at a certain time that causes physiological changes, the drug administration must be entered in the record in proper time sequence to understand the change in the physiological state of the patient.

ALARM, DIAGNOSTIC, AND FEEDBACK SYSTEMS

As sophistication in monitoring and the number of parameters measured increase, one is faced with interpreting the data. It has been clearly demonstrated in several centers that merely presenting data, raw or derived, does not necessarily improve patient care (14–17, 104, 105). The intellectual problem of deciding if a change has occurred in the patient's status, and if that change requires intervention, is one of considerable importance and one where the computer can help by organizing the data (92, 106).

There are three distinct types of computer-generated feedback. The first is an alarm system. Alarm systems can be based on single or multiple parameters based on data derived from physiological signals and/or manually entered data. The shortcomings of this type of simple approach to monitoring are pointed out by Raison (51) and Afifi (106). However, even these simple alarms have value (40). The second level of feedback can take two forms: (a) verbal feedback, suggesting to the physician or nurse the course of therapy that should be taken, e.g., drug drip rates, and (b) an automatic physical feedback control of the patient. Examples of the latter are a fluid and blood infusion system in use at the University of Alabama (14, 91), and drug infusion and respirator control systems proposed by several installations. The third type of feedback consists of taking derived data and making a diagnosis and suggesting therapy or procedures. Although this approach is in its formative stages (99), it has tremendous implications.

The implications of the latter two types of feedback systems are many. Not only do they provide a valuable assist to the person involved in the decision-making process, but they also establish criteria necessary for treatment of patients in acute situations. Capability of such a system provides ready access not only to the raw data and trends but also to clinically relevant decisions previously made in a manner not unlike the problem-oriented medical record system of Weed (107).

INTERACTION WITH OPERATORS

Critical to the success of any operator-oriented system is the human engineering. In the case of clinical physiological monitoring this is especially important, since the understanding, background, and training of the users is widely varied.

In the case of the intensive care unit, the user is normally a highly trained nurse with a little training in technical areas. In the surgical suite it is normally a highly trained and sophisticated physician who is making use of the information.

Use by personnel who are not actively, day-to-day involved in computer monitoring has been a major problem and will continue to be a challenge. Despite the capabilities of a computer system, if people using it don't understand its capability and don't know how to use the information it provides, there will be little use of available information. Therefore, major emphasis at all the centers where computerized monitoring is used is towards training physicians, nurses, and technicians to understand better the physiological basis of information made available to them.

EVALUATION AND COST STUDY

A good way to evaluate any clinical system is to look at its "cost-effectiveness." The "cost" part of this evaluation is rather straightforward; however, the "effectiveness" is considerably more difficult to quantitate. Recent cost studies of our intensive care system (40, 108) and others, mainly Cox (42) and Sheppard (92, 109), have shown the computerization cost to be relatively high. Charges for computer use are being made at a rate of about $19 per day in our intensive care unit and are being made at a rate of $50 per day at the University of Alabama (4). (Data is not available on the other units.)

Cost evaluation is but one of the methods of evaluation. Indexes such as mortality, morbidity, length of stay, and others are indicators of the effectiveness of the system, but, unfortunately, are influenced by so many other factors that it is almost impossible to verify the most important one. For the present, at least, we feel the medical-clinical judgment of the physician in establishing charge for service is the best index of value. Over the next year the Arthur D. Little Company will be evaluating computerized physiological monitoring at four sites under contract from the national Center for Health Systems Research and Development and the Public Health Service. The purpose of this study will be to document the system benefits, extent of use, and impact the system has made on information transfer, medical care, and cost structure in intensive care. This study by an independent outside group should give insight into the effectiveness of clinical physiological monitoring.

CONCLUSIONS—FUTURE

Physiological monitoring is gaining wide acceptance in clinical practice because it is a form of "preventive medicine." Monitoring and clinical response to monitor-generated information play an important role in "prevention" of catastrophic events in the critically ill.

The search for the most predictive physiological measures will continue. New instruments will enable clinical investigators to evaluate patients better and to assess the predictive worth of physiological parameters measured by the instrument. The economic constraints of physiological monitoring and the measurement of cost-effectiveness will play an ever-increasing role. Although computers are rather expensive monitoring devices at the moment, they should bring about improved monitoring at less cost by (a) decreasing complications and hence, length of stay, and (b) decreasing requirements for staff to perform sophisticated quantitative monitoring.

Technological developments alone are not enough to improve patient care. A concerted effort must be made to educate the entire staff (physicians, nurses, technicians, etc) to the significance of physiological measurements. Improvements in monitoring can best be made by physicians, nurses, technicians, engineers, and programmers working as a team.

LITERATURE CITED

1. Taylor, D. J. W. 1970. *Postgrad. Med. J.* 46:350–59
2. Stewart, J. S. S. 1970. *Postgrad. Med. J.* 46:339–43
3. Crook, J. 1970. *Postgrad. Med. J.* 46:374–77
4. Wolff, H. S. 1970. *Biomedical Engineering*, 139–58. New York: McGraw-Hill
5. Wolff, H. S. 1971. *Postgrad. Med. J.* 47:12–15
6. Hugenholtz, P. G. 1971. *Comp. Biomed. Res.* 4, #5, October:i–ii
7. Kirkendall, W. M., Burton, A. C., Epstein, F. H., Freis, E. D. 1967. *Circulation* 36:980–88
8. Geddes. L. A. 1970. *Measurement of Blood Pressure.* Chicago: Year Book Medical Pub. 192 pp.
9. Fink. B. R. 1970. *Anesth. Analg.* 49:204–10
10. Kirby, R. R., Kemmerer, W. T., Morgan, L. 1969. *Anesthesiology* 31(1):86–89
11. Sheppard, L. C., Johnson, T. S., Kirklin, J. W. 1971. *J. Assoc. Advan. Med. Instrum.* 5:146
12. Zorab, J. S. M. 1969. *Anesthesia* 24:431–37
13. Cohn, J. N. 1967. *J. Am. Med. Assoc.* 199:119–22
14. Sheppard, L. C., Kouchoukos, N. T., Kurtts, M. A., Kirklin, J. W. 1968. *Ann. Surg.* 168:596–604
15. Osborn, J. J., Beaumont, J. O., Raison, J. C. A., Russell, J., Gerbode, F. 1968. *Surgery* 64:1057–70
16. Warner, H. R. 1968. *Anesth. Analg.* 47:453–62
17. Warner, H. R., Gardner, R. M., Toronto, A. F. 1968. *Circulation* (Suppl. II) 37:67–74
18. Aslam, P. A. 1971. *Ann. Thorac. Surg.* 11:61–63
19. Mortensen, J. D. 1967. *Circulation* 35:1118–23
20. Gardner, R. M., Warner, H. R., Toronto, A. F., Gaisford, W. D. 1970. *J. Appl. Physiol.* 29:911–13
21. Shubin, H., Weil, M. H., Palley, N., Afifi, A. A. 1971. *Comp. Biomed. Res.* 4:460–73
22. Gardner, R. M., Hoecherl, A. W. 1971. *IEEE Trans. Bio-Med. Eng.* 18:60–65
23. Weissler, A. M., Garrard, C. L., Jr. 1971. *Mod. Conc. Cardiovasc. Dis.* 60:1–8
24. Hutter, A. M., Jr., Moss, A. J. 1970. *J. Am. Med. Assoc.*
25. Witham, R. G. 1970. *Rocky M. Med. J.* 67:57–59
26. Wilson, J. N., Owens, J. C. 1970. *Hosp. Med.* April, pp. 86–93
27. Meagher, P. F., Jensen, R. E., Weil, M. H., Shubin, H. 1966. *IEEE Trans. Biomed. Eng.* 13:54–57
28. Warner, H. R. 1969. *Comp. Biomed. Res.* 3:239–51
29. Swan, H. J. C., et al. 1970. *N. Engl. J. Med.* 283:447–51
30. Ganz, W. W. 1970. *Am. J. Cardiol.* 25:96
31. Rutherford, B. D., McCann, W. D., O'Donovan, T. P. B. 1971. *Circulation* 43:655–66
32. Yashar, J. J., Hallman, G. L., Leachman, R. D., Cooley, D. A. 1971. *J. Thorac. Cardiovasc. Surg.* 61:724–28
33. Starmer, C. F., Clark, D. O. 1970. *J. Appl. Psychol.* 28:219–20
34. Ramo, B. W. et al. 1970. *Circulation* 65:567–77
35. Weil, M. H. 1970. *Phys. Med. Biol.* 15:184
36. Mortensen, J. D.. Anderson, L. H. 1968. *J. Thorac. Cardiovasc. Surg.* 56:510–19
37. Fox, I. J., Wood, E. H. 1960. *Med. Phys.* 3:163–78
38. Warner, H. R., Gardner, R. M.,

Pryor, T. A., Day. W. C., Stauffer, W. M. 1970. *UCLA Forum Med. Sci. n10*:409–18
39. Wessel, H. A., Paul, M. H., James, G. N., Grahn, A. R. 1971. *J. Appl. Physiol.* 30:643–52
40. Gardner, R. M. 1971. *San Diego Biomed. Symp., 1971* 10:151–59
41. Rutherford, B. D., Warner, H. R., Gardner, R. M. 1971. Submitted for publication
42. Cox, J. R., Jr., Logue, R. D. 1971. *Comp. Biomed. Res.* 4:447–59
43. Cox, J. R., Jr., Holle, F. M., Fozzard, H. A., Oliver, G. C., Jr. 1968. *IEEE Trans. Biomed. Eng.* 15: 128–29
44. Geddes J. S., Warner, H. R. 1971. *Comp. Biomed. Res.* 4:493–508
45. Bonner, R. E., Schwetman, H. D. 1968. *Comp. Biomed. Res.* 1:387–407
46. Crockett, G. S. 1970. *Postgrad. Med. J.* 46:378–79
47. Pryor, T. A., Russell, R., Budkin, A., Price, W. G. 1969. *Comp. Biomed. Res.* 2:537–48
48. Webb, G. N., Rogers, R. E. 1966. *IEEE Spectrum* 3(6):77–87
49. Pontoppidan, H., Laver, M. B., Geffin, B. 1970. *Advan. Surg.* 4: 163–254
50. Latimer, R. G., Dickman, M., Day, W. C., Gunn, J. L., Schmidt, C. D. 1971. *Am. J. Surg.* 122:622–32
51. Raison, J. C. A., Beaumont, J. O., Russell, J. A. G., Osborn, J. J., Gerbode, F. 1968. *Comp. Biomed. Res.* 1:556–64
52. Elliott, S. E., Miller, C. W., Armstrong, W. T., Jr., Osborn, J. J. 1970. *Am. Heart J.* 79:215–22
53. Puryear, G. H., Osborn, J. J., Beaumont, J. O., Gerbode, F. 1969. *Ann. Surg.* 170:900–9
54. Raison, J. C. A., Chir, B., Osborn, J. J., Beaumont, J. O., Gerbode, F. 1970. *Ann. Surg.* 171:471–84
55. Deal, C., Osborn, J. J., Ellis, E., Gerbode, F. 1968. *Ann. Surg.* 167: 73–77
56. Beaumont, J. O. 1969. *Datamation* 15(5):50–55
57. Osborn, J. J., Beaumont, J. O., Raison, J. C. A., Abbott, R. P. 1969. *Comp. Biomed. Res.* 3:207–37
58. Osborn, J. J., et al. 1971. *Surgery* 69:24–28
59. Hilberman, M., Schill, J. P., Peters, R. M. 1969. *J. Thorac. Cardiovasc. Surg.* 58:821–28
60. Peters, R. M. et al. 1971. *Description of Thoracic Surgery Monitoring Project*. Dept. Surg. Univ. of Calif. San Diego, La Jolla, Calif. May, 1971
61. Peters, R. M., Hilberman, M. 1971. *Surgery* 70:280–87
62. Lewis, F. J., et al. 1970. *Surg. Gynecol. Obstet.* 130:333–41
63. Lewis, F. J., Shimizu, T., Schofield, A. L., Rosi, P. S. 1966. *Ann. Surg.* 164:547–57
64. Dammann, J. R., Jr., Wright, D. J., Updike, O. L. 1969. *Dis. Chest* 55:240–44
65. Dammann, J. R., Wright, D. J., Updike, O. L. 1969. *Biomed. Sci. Instr.* 5:17–27
66. Dammann, J. F., Updike, O. L., Wright, D. J. 1970. *Proc. San Diego Biomed. Symp.* 9:57–64
67. Comper, A. 1969. *Surg. Bus.* May, pp. 33–35
68. Vallbona, C., Pevny, E., McMath, R. 1971. *Comp. Biomed. Res.* 4:623–33
69. Clark, J. S., Gardner, R. M. 1968. *Ann. Conf. Eng. Med. Biol., 21st 1967* 10:17.7
70. Eberhart, R. C. 1968. *Biomed. Sci. Instr.* 4:197
71. Clark, J. S., Veasy, L. G., Jung, A. L., Jenkins, J. L. 1971. *Comp. Biomed. Res.* 4:262–74
72. Veasy, L. G., Clark, J. S., Jung, A. L., Jenkins, J. L. 1971. *Pediatrics* 48: 5–17
73. Kampine, J. P., Macur, R. A., Coon, R. L., Bernard, S. W. C., Henschel, E. O. 1971. Presented at Anesthesia Society of America Meeting, Oct., 1971
74. Cook, C. D. 1971. *Pediatrics* 48:1–2
75. Tulou, P. P., Walsh, P. M. 1970. *Am. Rev. Resp. Dis.* 102:921–26
76. Field, G. B., Jones, G., McFadden, E. R., Jr. 1971. *J. Appl. Physiol.* 31:490–96
77. Hale, F. C., Hanish, H. M., Olsen, C. R. 1969. *Am. Rev. Resp. Dis.* 99:282–84
78. Neville, D. J., Gordon, A. S. 1971. *J. Assoc. Advan. Med. Instrum.* 5A, #2:135
79. Jackovitch, T., Eberhart, R. C. 1971. *San Diego Biomed. Symp. 1971.* 10:47–52
80. Gardner, R. M., Olsen, K. R., Waters, L. P., Schmidt, C. D. 1971. *Ann. Conf. Eng. Med. Biol., 24th 1970* 13:73
81. Geddes, L. A., Hoff, H. E., Michman, P. M., Hinds, M., Baker, L. 1962.

Aerosp. Med. 3:891–95
82. Gump, F. E., Kinney, J. M., Price, J. B. 1970. *J. Surg. Res.* 10:613–27
83. Woldring, S. 1970. *J. Assoc. Advan. Med. Instrum.* 4:43–56
84. Fowler, K. T. 1969. *Phys. Med. Biol.* 14:185–99
85. Osborn, J. J., Elliott, S. E., Segger, F. J., Gerbode. F. 1969. *Med. Res. Eng.* 8:19–23
86. Mead, J. 1961. *Physiol. Rev.* 41:281–330
87. Johnson, C. C., Palm, R. D., Stewart, D. C., 1971. *J. Assoc. Advan. Med. Instrum.* 5:77–83
88. Johnson, C. C., Peter, W. G., Cole, J. S., Martin, W. E. 1971. *Ann. Conf. Eng. Med. Biol., 24th 1970* 13:251
89. Dardik, H., Dardik, I., Laufman, H. 1970. *Surg. Gynecol. Obstet.* 131: 1157–60
90. Owens, G., Belmusto, L., Woldring, S. 1969. *J. Neurosurg.* 30:110–15
91. Sheppard, L. C., Kouchoukos, N. T., Acton, J. C., Jr., Kirklin, J. W. 1970. *San Diego Biomed. Symp. 1970*
92. Sheppard, L. C., Kouchoukos, N. T., Kirklin, J. W. 1971. *Proc. Ser. Excerpta Med. Found. Dusseldorf 1972.* In press
93. Meagher, P. F., Jensen, R. E., Pearcy, M. G., Weil, M. H. Shubin, H. 1966. *Med. Res. Eng.* 5:38–39
94. Joly, H. R., Weil, M. H. 1969. *Circulation* 39:131–38
95. Friedlander, G. D. 1971. *IEEE Spectrum* 8(9):40–51
96. Starmer, C. F., McIntosh, H. D., Whalen, R. E. 1971. *N. Engl. J. Med.* 284:181–86
97. Bruner, J. M. R. 1967. *Anesthesiology* 28:396–425
98. Whalen, R. E.. Starmer, C. F. 1967. *Mod. Conc. Cardiovasc. Dis.* 34: 7–12
99. Warner, H. R., Olmsted, C. M., Rutherford, B. D. 1972. *Comp. Biomed. Res.* 5:65–74
100. Pryor, T. A., Gardner, R. M., Day, W. C. 1968. *Proc. Am. Fed. Inf. Process. Soc.* 33:809–16
101. Macdonald, L. K., Gardner, R. M., Pryor, T. A., Day, W. C. 1971. *Comp. Biomed. Res.* 3:586–603
102. Warner, H. R. 1970. *Comp. Biomed. Res.* 3:285–88
103. Warner, H. R., Morgan, J. D. 1970. *Comp. Biomed. Res.* 3:464–76
104. Stewart, D. H., Erbech, D. H., Shubin, H. 1968. *Proc. Am. Fed. Inf. Process. Soc.* 33:797–807
105. Shubin, H., Weil, M. H. 1966. *Ann. Intern. Med.* 65:453–60
106. Afifi, A. A., Rand, W. M., Palley, N. A., Shubin, H., Weil, M. H. 1971. *Comp. Biomed. Res.* 4:329–39
107. Weed, L. L. 1970. *Medical Records, Medical Education and Patient Care,* 409–18. Chicago: Year Book Medical Pub. 273 pp.
108. Macdonald, L. K. 1971. *Hospitals, J.A.H.A.* 45:72–75
109. Sheppard, L. C., Kouchoukos, N. T., Kirklin, J. W. 1972. *Proc. Nat. Acad. Sci. Symp. 1971.* In press
110. Fox, C. L., Jr., Nahas, G. G. 1969. *Body Fluid Replacement in the Surgical Patient.* New York: Grune & Stratton. 344 pp.
111. Ruch, T. C., Patton, H. D. 1965. *Physiol. Biophys.,* p. 680